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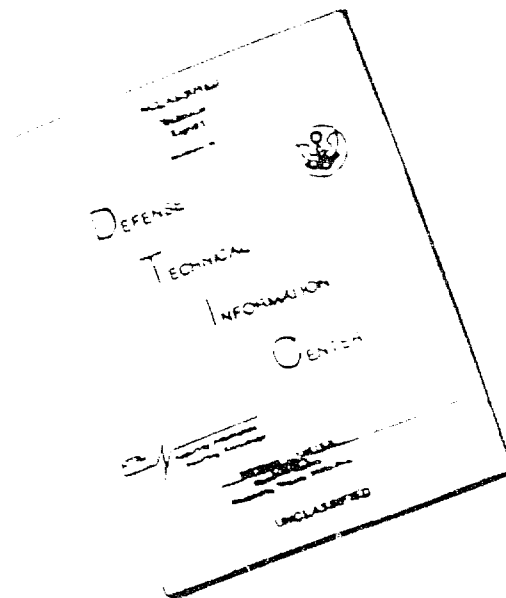
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**Resistance as Dissipation into Many  
Reactive Circuits: Landau Damping  
and Nyquist's Noise Theorem**

by  
**O. Buneman**

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**Technical Report No. 104-4  
November 23, 1960**

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LANDAU DAMPING AND NYQUIST'S NOISE THEOREM

by

O. Buneman

Technical Report No. 104-4  
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Electron Devices Laboratory  
Stanford Electronics Laboratories  
Stanford University  
Stanford, California

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UNITED STATES AIR FORCE  
Bedford, Massachusetts

In general,  $B$  depends on  $\Omega$ . The case of constant  $B$  leads to divergence of the integral but this simple and interesting case can be approximated arbitrarily closely, without loss of convergence, by taking

$$B = \frac{B_0}{1 + \Omega^2/\Omega_0^2}$$

with sufficiently large  $\Omega_0$ . The integration is effected by completing the path around a large semi-circle in the upper half-plane and contracting around the only pole at  $\Omega = +j\Omega_0$ . The pole at  $\Omega = -js$  is in the lower half-plane, by the rules of Laplace transform theory ( $\text{Re } s > 0$ ).

The result,

$$Y = \frac{\pi B_0}{2 \left( 1 + \frac{s}{\Omega_0} \right)},$$

shows that the effective impedance of our network consists of a resistance  $2/\pi B_0$  and an inductance  $2/\pi B_0 \Omega_0$ . The latter vanishes in the limit  $\Omega_0 \rightarrow \infty$ . The simulation of resistance by reactive elements is thus established. The conductance with  $\Omega_0 \neq \infty$  is

$$\frac{1}{2} \frac{\pi B_0}{1 + \omega^2/\Omega_0^2} = \frac{1}{2} \pi B(\omega)$$

and this formula for the conductance is obtained also with more general forms of  $B(\Omega)$  than that assumed here.

### 3. Applications of the Resistance Model.

Our picture of dissipation assists the understanding of Landau<sup>1</sup>

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<sup>1</sup>L. Landau, J. Phys. USSR 10, 25(1946).

damping of disturbances with wave number  $k$  in a collision-free plasma; the electron streams passing through the plasma with their continuously distributed velocities  $v$  provide a continuous range of resonance frequencies  $\Omega = kv$ .

Moreover, Nyquist's<sup>2</sup> noise theorem is readily obtained from this resonant-circuit model of resistance. If the network is shorted at the port of measurement after having been in thermal contact with the surroundings, each circuit will be left oscillating with energy

$$\frac{1}{2} L_v |I_v|^2 + \frac{1}{2} C_v |V_v|^2 = L_v |I_v|^2 = C_v |V_v|^2 = KT$$

from which we deduce

$$|I|^2 = \frac{KT}{L_v} = KTB \, d\Omega = \frac{2}{\pi} KTG \, d\Omega$$

where  $G$  is the "conductance" identified above. This is Nyquist's formula.

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<sup>2</sup>H. Nyquist, P. R. 32, 110 (1928).



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